Ministry/Organization Name/Student Innovation: Department of Space, Indian Space Research Organisation

PS Code: SS612

Problem Statement Title: Prediction of TEC Variations with Artificial Intelligence using Space Weather Data

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Institute Code (AISHE): C- 25248

Problem Category: Software

Theme Name: Disaster Management

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Problem Statement

The ionospheric electron density is sensitive to the space weather parameters like Sunspot numbers, F10.7, Interplanetary magnetic field etc. and shows variation with respect to them. These parameters are detected and measured at L1 point (currently by ESA / NASA satellites) and are transmitted to earth. The above mentioned parameters affect the ionospheric TEC, which in turn shows abrupt variations and deviations from the nominal characteristics. Therefore, these unconventionalities, which are typically observed during solar and geomagnetic storms, are necessary to be identified. This is also important, because the performance of the GNSS system, which is currently driving millions of applications, are also affected by the ionospheric variabilities. So, prediction of the TEC provides a handle to take necessary actions to avoid or mitigate the resultant impairments arising out of the above facts. For the purpose, the time sequence of space-weather parameters, along with the local time, location, season, date etc. can be related to the same for the vertical TEC and a definitive relationship can be established using Artificial Intelligence (AI) methods, like neural networks or other deep learning algorithms.The problem requires the development of the proper AI algorithm to use the available space weather and other data to predict the TEC variations at one particular location on the earth, preferably over the geomagnetic equator.

Objective

Making a web application that helps to :

1. To visualize global and regional TEC variations and investigate the anomalies.
2. To predict the TEC by Machine Learning models trained with time sequence weather data recorded by GNSS receiver over years.
3. To measure and improve accuracy of prediction so that disruptive effect of unconventional variations on satellite communication can be mitigated
4. To observe the impact of solar and geomagnetic storms on TEC variations and also find its correlation with weather data.
5. To compare various ML models and find out pros and cons.

Total Electron Count - Introduction

The Total Electron Content (TEC) is the total number of electrons present along a path between a radio transmitter and receiver. Radio waves are affected by the presence of electrons. The more electrons in the path of the radio wave, the more the radio signal will be affected. For ground to satellite communication and satellite navigation, TEC is a good parameter to monitor for possible space weather impacts.

TEC is measured in electrons per square meter. By convention, 1 TEC Unit TECU = 10^{16} electrons/m^2. Vertical TEC values in Earth's ionosphere can range from a few to several hundred TECU.

The TEC in the ionosphere is modified by changing solar Extreme Ultra-Violet radiation, geomagnetic storms, and the atmospheric waves that propagate up from the lower atmosphere. The TEC will therefore depend on local time, latitude, longitude, season, geomagnetic conditions, solar cycle and activity, and troposphere conditions. The propagation of radio waves is affected by the ionosphere. The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the TEC between the transmitter and the receiver. At some frequencies the radio waves pass through the ionosphere. At other frequencies, the waves are reflected by the ionosphere.

Data Description

1. Ionex Format

The VTEC is read from a IONEX file. A stream contains, for a given day, the values of the TEC for each hour of the day. Values are given on a global 2.5° x 5.0° (latitude x longitude) grid.

A bilinear interpolation is performed the case of the user initialize the latitude and the longitude with values that are not contained in the stream.

A temporal interpolation is also performed to compute the VTEC at the desired date.

IONEX files are obtained from The Crustal Dynamics Data Information System.

The files have to be extracted to UTF-8 text files before being read by this loader.

Ionex Format

```
     1.0            IONOSPHERE MAPS     MIX                 IONEX VERSION / TYPE
cmpcmb v1.2          GRL/UWM            16-jan-20 13:02     PGM / RUN BY / DATE
ionex file containing IGS COMBINED Ionosphere maps          COMMENT
global ionosphere maps for day 001, 2020                    DESCRIPTION
IONEX file containing the COMBINED IGS TEC MAPS and DCBs    DESCRIPTION
      IONEX files of the following IAACs were combined: cod DESCRIPTION
                                                        esa DESCRIPTION
                                                        jpl DESCRIPTION
                                                        upc DESCRIPTION
Contact address: Andrzej Krankowski                         DESCRIPTION
                 Geodynamics Research Laboratory            DESCRIPTION
                 University of Warmia and Mazury (GRL/UWM)  DESCRIPTION
                 Oczapowski St. 1                           DESCRIPTION
                 10-957-Olsztyn, POLAND                     DESCRIPTION
                 e-mail:  kand@uwm.edu.pl                   DESCRIPTION
                                                            DESCRIPTION
  2020     1     1     0     0     0                        EPOCH OF FIRST MAP
  2020     1     2     0     0     0                        EPOCH OF LAST MAP
  7200                                                      INTERVAL
    13                                                      # OF MAPS IN FILE
  COSZ                                                      MAPPING FUNCTION
     0.0                                                    ELEVATION CUTOFF
combined TEC calculated as weighted mean of input TEC valuesOBSERVABLES USED
   392                                                      # OF STATIONS
    32                                                      # OF SATELLITES
  6371.0                                                    BASE RADIUS
     2                                                      MAP DIMENSION
   450.0 450.0   0.0                                        HGT1 / HGT2 / DHGT
    87.5 -87.5  -2.5                                        LAT1 / LAT2 / DLAT
  -180.0 180.0   5.0                                        LON1 / LON2 / DLON
    -1                                                      EXPONENT
TEC values in 0.1 tec units;  9999, if no value available   COMMENT
DCB values in nanoseconds, reference is Sum_of_SatDCBs = 0  COMMENT
```

```
   95   88   82   78   76   74   75   80   87   92   95   96   95   94   90   84
   77   70   65   60   58   55   52   47   42   39   34   30   27   28   32   35
   35   36   36   36   35   34   36   47   63   79   92  103  114  126  138  148
  154  158  161  168  171  170  173  179  189
    12.5-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  193  206  223  241  247  255  265  264  239  211  188  164  145  133  122  110
  101   94   88   85   84   84   88   95  102  105  103  100   98   95   91   83
   76   70   63   57   55   53   49   45   41   37   33   29   27   29   34   36
   37   36   36   35   34   33   37   49   67   84   97  109  121  135  148  158
  163  167  169  172  175  175  177  183  193
    10.0-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  195  207  222  243  252  261  273  275  257  230  207  185  165  149  137  122
  109  102   97   95   95   97  104  111  116  113  106   98   93   90   86   80
   74   68   62   56   54   51   49   45   41   38   35   31   30   31   35   37
   37   37   35   34   32   33   38   52   71   88  101  111  125  140  154  164
  169  172  172  175  175  175  177  185  195
     7.5-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  194  207  218  233  242  251  262  270  261  240  219  202  183  167  153  135
  121  113  108  108  109  112  121  127  126  115  103   93   86   82   80   76
   72   68   62   58   56   53   52   48   44   41   38   34   32   33   35   37
   37   36   35   33   32   33   41   56   74   91  102  111  125  140  156  165
  170  172  172  173  173  173  176  183  194
     5.0-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  192  205  213  219  223  230  239  249  248  237  222  210  196  182  168  150
  133  124  120  122  123  127  133  139  134  115   99   87   80   77   76   75
   74   70   66   62   60   58   56   53   49   46   42   37   36   35   37   38
   38   36   35   34   33   35   44   59   78   92  101  109  123  139  154  163
  167  169  170  171  170  170  174  182  192
     2.5-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  191  203  208  208  208  210  215  224  228  224  216  209  201  192  180  164
  146  135  132  134  137  140  143  143  135  116   98   85   79   77   78   79
   78   75   72   68   66   63   61   57   54   51   47   42   40   39   40   41
   40   38   35   34   34   38   47   63   80   92   99  106  120  135  149  158
  162  164  167  167  166  166  172  180  191
     0.0-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
  191  204  209  206  202  199  200  205  209  208  205  203  200  195  186  172
  156  146  141  144  147  149  148  144  133  117  101   89   84   84   84   84
   84   82   78   74   72   68   65   61   58   55   52   47   43   42   43   44
   42   39   36   35   36   40   50   65   81   92   98  105  116  129  142  151
  156  159  162  164  162  164  169  179  191
```

Data Description

2. Rinex Format

Receiver Independent Exchange Format (**RINEX**) is a data interchange format for raw satellite navigation system data. This allows the user to post-process the received data to produce a more accurate result — usually with other data unknown to the original receiver, such as better models of the atmospheric conditions at time of measurement.

The final output of a navigation receiver is usually its position, speed or other related physical quantities. However, the calculation of these quantities are based on a series of measurements from one or more satellite constellations. Although receivers calculate positions in real time, in many cases it is interesting to store intermediate measures for later use. RINEX is the standard format that allows the management and disposal of the measures generated by a receiver, as well as their off-line processing by a multitude of applications, whatever the manufacturer of both the receiver and the computer application.

The RINEX format is designed to evolve over time, adapting to new types of measurements and new satellite navigation systems.

Rinex Format

```
     3.02           OBSERVATION DATA    M: MIXED            RINEX VERSION / TYPE
Leica Infinity 2.1                      20170330 192656 UTC PGM / RUN BY / DATE
2                                                           MARKER NAME
2                                                           MARKER NUMBER
GEODETIC                                                    MARKER TYPE
                                                            OBSERVER / AGENCY
3248294             LEICA GS16          6.13                REC # / TYPE / VERS
                    LEIGS16         NONE                    ANT # / TYPE
   808630.6740 -4918582.2152  3966416.8757                  APPROX POSITION XYZ
        1.7998        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G   16 C1C L1C D1C S1C C2S L2S D2S S2S C2W L2W D2W S2W C5Q  SYS / # / OBS TYPES
       L5Q D5Q S5Q                                          SYS / # / OBS TYPES
R    8 C1C L1C D1C S1C C2P L2P D2P S2P                      SYS / # / OBS TYPES
DBHZ                                                        SIGNAL STRENGTH UNIT
     5.000                                                  INTERVAL
  2017     02     24     18     46   50.0000000     GPS     TIME OF FIRST OBS
  2017     02     24     19     20    5.0000000     GPS     TIME OF LAST OBS
     0                                                      RCV CLOCK OFFS APPL
G L2S -0.25000                                              SYS / PHASE SHIFT
G L2X -0.25000                                              SYS / PHASE SHIFT
R L2P  0.25000                                              SYS / PHASE SHIFT
E L8Q -0.25000                                              SYS / PHASE SHIFT
 C1C  -71.940 C1P  -71.940 C2C  -71.940 C2P  -71.940        GLONASS COD/PHS/BIS
    17                                                      LEAP SECONDS
                                                            END OF HEADER
> 2017 02 24 18 46 50.0000000  0 15
G03    21918730.000 115183701.61917         952.709          46.850    21918734.200  89753546.96317         742.370          44.700    21918734.300  89753549.95916
G14    21149467.700 111141203.35418       -1353.300          49.200                                                                        21149469.340  86603539.47316
G16    22084769.920 116056252.94717        3429.903          47.100                                                                        22084772.220  90433448.46816
G22    21509499.440 113033183.37818        -283.437          49.150                                                                        21509499.320  88077803.93916
G23    24281434.560 127599798.28217        3152.119          43.600                                                                        24281436.380  99428417.08215
G25    24183125.240 127083178.30717       -3490.522          43.350    24183130.160  99025866.50017       -2719.890          42.050    24183130.400  99025868.49016
G26    20762467.020 109107500.80518        1575.543          50.300    20762471.560  85018844.70118        1227.697          47.550    20762471.900  85018847.69817
G29    23908430.020 125639642.15416         988.559          37.050    23908435.400  97901048.87215         770.309          32.300    23908434.920  97901042.89814
G31    20879667.800 109723393.74418       -1523.864          51.100    20879668.480  85498750.44217       -1187.427          45.550    20879668.180  85498750.43416
G32    22828108.760 119962521.61117       -2669.465          46.550    22828114.320  93477303.09017       -2080.104          43.150    22828114.340  93477303.08616
R02    19139367.300 102131329.48318        -592.353          51.150    19139371.560  79435492.48317        -460.719          46.350
R03    21201191.800 113491637.28118        3294.613          47.800    21201194.240  88271280.28817        2562.476          44.900
R11    22856297.160 122137118.42817       -3572.543          44.800    22856302.060  94995557.49017       -2778.647          42.900
R12    19617304.020 104792114.13418       -1509.670          49.700
R13    20848624.420 111330490.93017        2207.254          44.150    20848629.600  86590397.95217        1716.754          42.000
> 2017 02 24 18 46 55.0000000  0 15
G03    21917824.400 115178942.66907         949.587          47.000    21917828.620  89749838.68007         739.937          44.850    21917828.700  89749841.67606
G14    21150755.880 111147972.70408       -1355.327          49.150                                                                        21150757.520  86608814.29106
G16    22081506.980 116039106.20807        3427.926          46.950                                                                        22081509.260  90420087.40906
G22    21509770.220 113034606.29908        -286.646          49.100                                                                        21509770.080  88078912.70706
G23    24278435.100 127584036.10007        3151.794          44.350                                                                        24278436.920  99416134.88005
G25    24186446.520 127100631.83807       -3491.784          42.900    24186451.480  99039466.65807       -2720.871          41.600    24186451.700  99039468.64005
G26    20760968.900 109099628.19208        1572.565          50.200    20760973.440  85012710.20508        1225.378          47.500    20760973.780  85012713.20507
G29    23907490.140 125634703.13806         985.689          37.650    23907495.460  97897200.32505         768.073          32.700    23907495.000  97897194.32804
G31    20881117.880 109731013.95008       -1525.104          51.050    20881118.540  85504688.26707       -1188.394          45.550    20881118.260  85504688.26107
G32    22830649.020 119975870.72507       -2671.000          46.650    22830654.560  93487704.99107       -2081.300          43.000    22830654.580  93487704.99506
```

Models for Predicting Variations

Several global TEC prediction models have been constructed and evaluated, such as -

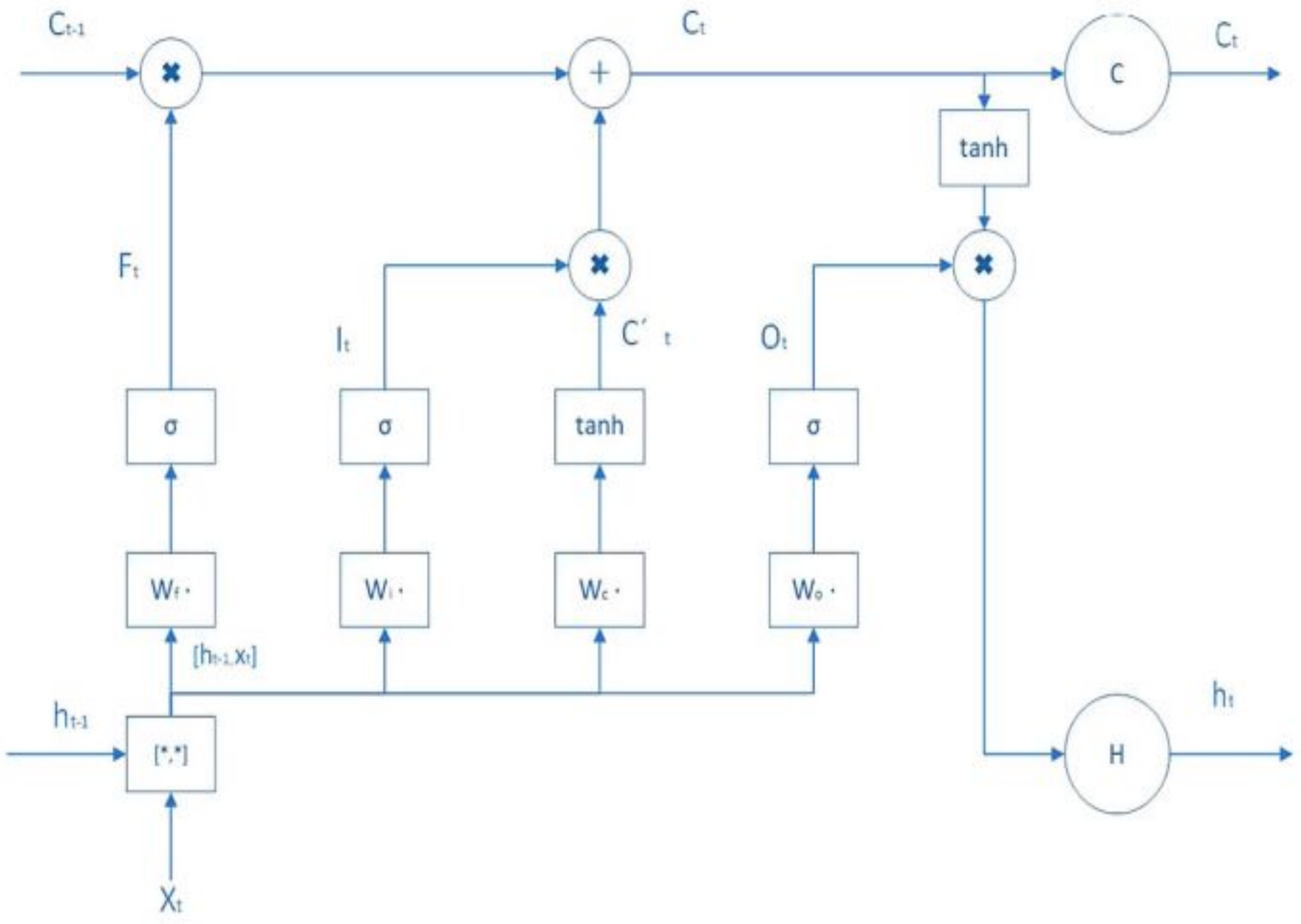
1. Klobuchar model for estimating Global Positioning System (GPS) signal delay (Klobuchar 1987)
2. International Reference Ionosphere (IRI) model for estimating specified ionospheric parameters
3. NeQuick model for estimating electron density
4. NeQuick-G model adopted by the Galileo system for its single-frequency users

But due to different drawbacks of other models we use Long Short Term Memory (LSTM) model

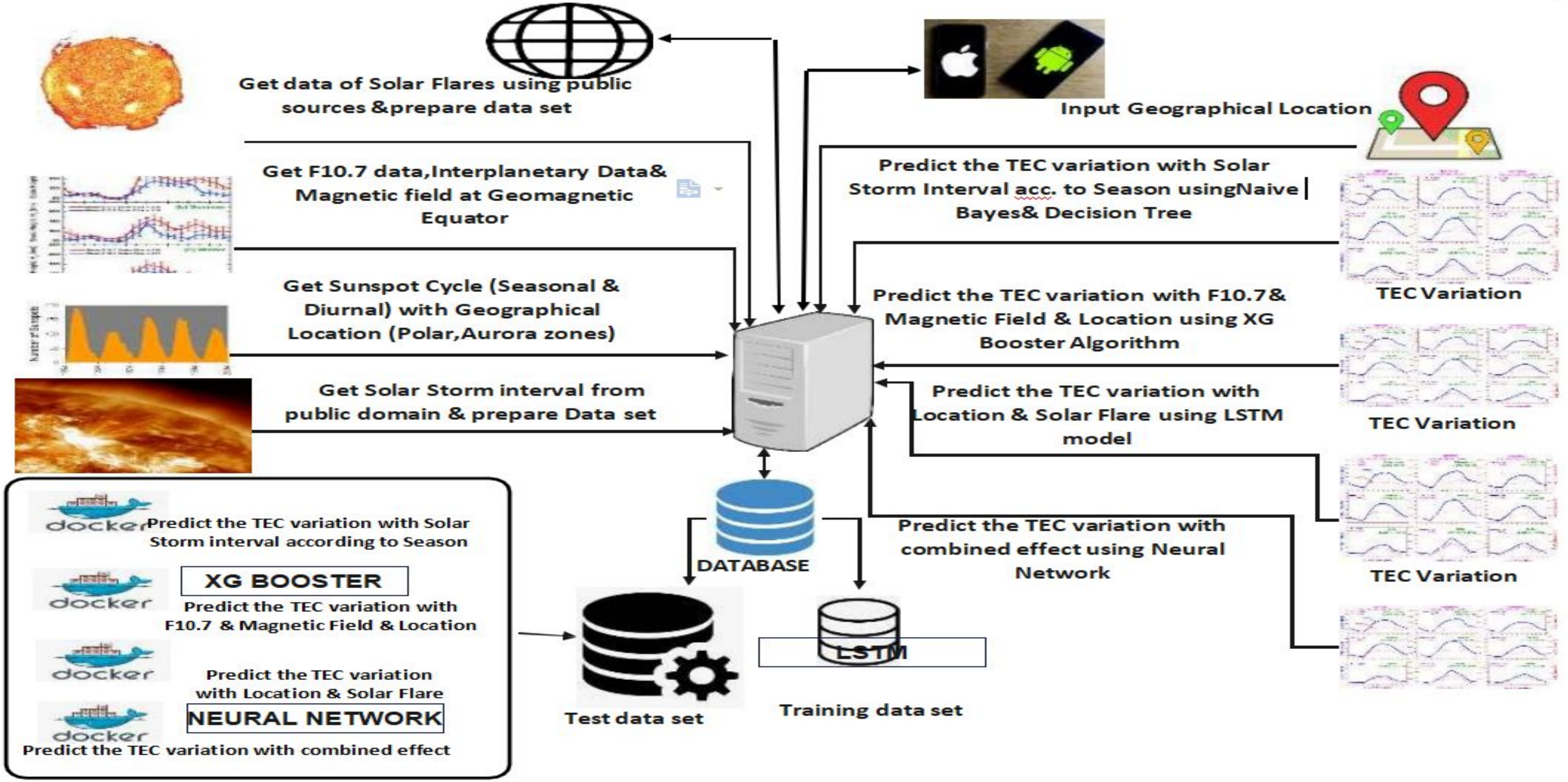
LSTM MODEL

Long Short Term Memory (LSTM) is a type of Recurrent Neural Network (RNN), and it is mainly used to model time series and its long-term dependence. On the basis of simple recurrent networks, LSTM adds memory cells to each neuron unit of the hidden layer to store information for a long period of time, so that the memory in formation in the time series is controllable. Using three gates (i.e., forget, input, and output gates), LSTM can select the amount of information of the previous cell to be included, so that it is capable of learning both long- and short-term dependencies between features, which is beneficial to the prediction of time series. The hidden layer of LSTM has three types of gate: forget gate (ft), input gate (it), and output gate (ot); C and H represent cell state and output, respectively, and subscripts $t-1$ and t represent previous and current time, respectively. The forget gate determines to what extent to forget the previous information. The input gate determines how much of the input at the current time the cell state retains to avoid the input of useless information. The output gate decides what the current output value should be.

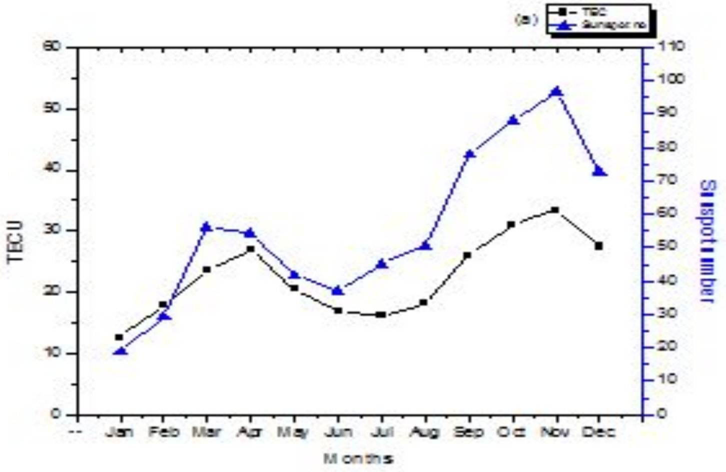
Structure of LSTM model

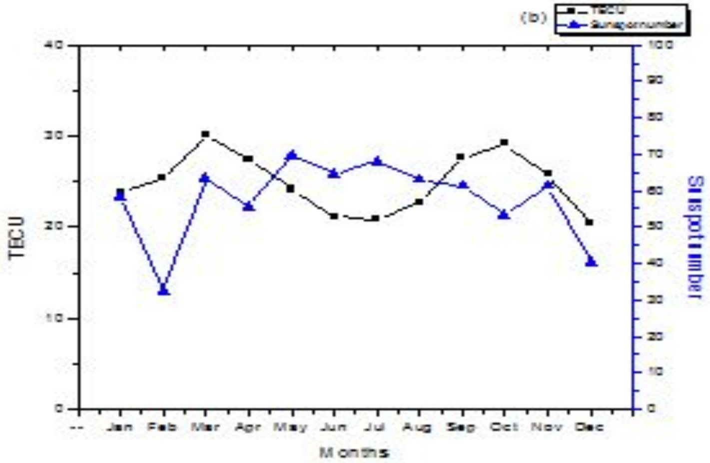


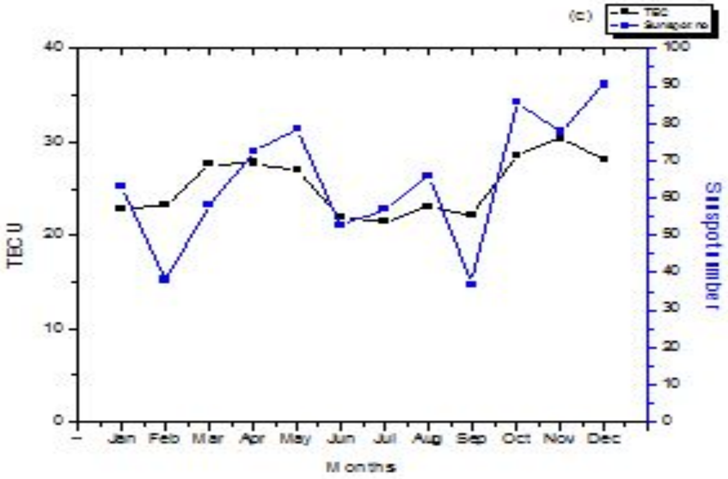
Implementation

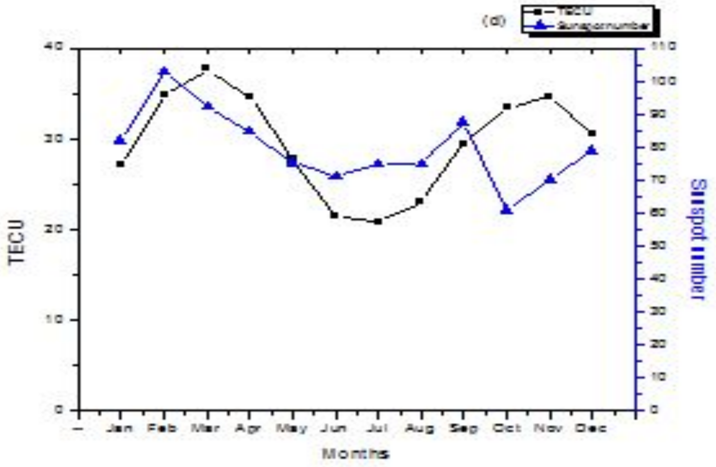


Results Description









References

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Thank you!